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13. ABSTRACT *(Maximum 200 words)*
Prolonged exhaustive physical exertion is often predicted to result in reduced performance capacity ("overtraining"), through mechanisms of tissue breakdown and inadequate time for full recuperation. This is of importance in military operations, where sustained performance is a typical requirement. We had the opportunity to test the hypothesis that highly motivated men pushed to the limits of their endurance capacity would suffer physical breakdown. Two, 25 year old, Norwegian Navy, Sea, Air and Land Soldiers, (SEALS) completed an unsupported 2928 kilometer south-to-north ski-trek across Greenland in 86 days. The trek involved ski-marching, for 9 hours a day, pulling sleds (150 kg starting load) with all of their food, fuel and supplies. Both SEALs ate an energy-dense diet estimated at 6000 kcal per day. The two volunteers were tested 14 days pre- and 4 days post-trek using anthropometric, physiological, and performance measures. Pre-trek testing showed them to be aerobically and anaerobically fit and to have high lean body masses. Total daily energy expenditure (TDEE), based on doubly-labeled water, reached 6750 and 8260 kcal/d for the two men during the most demanding phase of the trek and other samples showed TDEEs of ; 3500 to 4940 kcal/d. Both men lost body weight, with the changes primarily reflecting loss of fat energy stores, finishing the trek with fat stores of approximately 13% body fat. Most physical performance measures showed no significant loss of physical capacity as a result of prolonged exertion. However, anaerobic tests were significantly impaired following the trek, probably reflecting a detraining effect and possibly including some component of fast twitch muscle loss as previously reported in other prolonged military ski treks. This study documents that well-trained and experienced long-distance ski-trekkers who eat a high-calorie diet can perform long and arduous treks in severe conditions, with relatively minor and acceptable losses in lean body mass and physical capability.

14. SUBJECT TERMS
Greenland, ski-trekking, body composition, anthropometry, energy expenditure, physical performance, arctic, expedition, endocrine markers, glucose tolerance test

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USARIEM TECHNICAL REPORT T02-1

EFFECTS OF A WORLD RECORD UNSUPPORTED SKI TREK ACROSS GREENLAND (THE G2 EXPEDITION) ON PHYSICAL PERFORMANCE AND BODY COMPOSITION

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TABLE OF CONTENTS

ABOUT THE AUTHORS

NOTE: The trek was planned by the subjects themselves, with data collection added as an afterthought. "The project" referred to below encompasses only the scientific testing of the Greenland ski trekkers as well as the data analysis and report writing. The authors of this report claim no credit or responsibility for planning or execution of the trek itself.

Peter Frykman conducted key coordination and data collection for this project, served as the primary contact with the research subjects, and was the primary author of the final report.

Everett Harman wrote the protocol and consent form, served as the Principal Investigator, designed physical performance tests and collected data.

John Patton provided oversight and guidance for the entire project, and provided input to protocol design and performance tests.

Per Kristian Opstad initiated this project, participated fully in protocol development, attended testing procedures at the US Army Research Institute of Environmental Medicine (USARIEM), and coordinated all aspects of the project that occurred outside of the United States.

Reed Hoyt and James DeLany worked out procedures for self-administration of doubly-labeled water doses and measured energy expenditures of the subjects.

Karl Friedl proposed and arranged resources for the project, assisted in writing the protocol, attended initial data collection, and assisted in analyzing results and writing the final report.

LIST OF FIGURES AND TABLES

ACKNOWLEDGMENTS

The authors would like to acknowledge the unselfish help provided by Robert Mello for his technical expertise in conducting the aerobic and anaerobic capacity tests and SPC Randall Bills for attention to the many logistical difficulties during testing.

The photographs used in this report are the property of Rune Gjeldnes and Torry Larsen and are used with their permission.

EXECUTIVE SUMMARY

Prolonged exhaustive physical exertion is often predicted to result in reduced performance capacity ("overtraining"), presumably through mechanisms of tissue breakdown and inadequate time for full recuperation. This is of importance in military operations, where sustained performance is a typical requirement. It is also important for prediction of adequate recovery times before soldiers are sent on subsequent missions. We had the opportunity to test the hypothesis that highly motivated men pushed to the limits of their endurance capacity would suffer physical breakdown. A comparable test of human limits could not have been ethically constructed for the sole purpose of research; this trek was planned by the subjects themselves, with observational data collection added as an afterthought. Two, 25 year old, Norwegian Navy, Sea, Air and Land Soldiers, (SEALS) completed an unsupported 2928 kilometer south-to-north ski-trek across Greenland in 86 days. The trek involved ski-marching, typically for 9 hours a day, pulling sleds with all of their food, fuel and supplies. These initially weighed 150 kg. Both SEALs ate an unusual energy-dense diet estimated at 6000 kcal per day. The two volunteers were tested 14 days pre- and 4 days post-trek using anthropometric, physiological, and performance measures. Pre-trek testing showed them to be aerobically and anaerobically fit and also to have high lean body masses. Total daily energy expenditure (TDEE), based on doubly-labeled water (DLW), was variable across the three periods tested. In the initial period, peak levels reached 6750 and 8260 kcal/d for the two men; in a two week sample during the main period of travel on flat terrain, TDEE was 3500-3850 kcal/d; in the final period, with more rugged terrain and during a concerted push to finish, TDEE averaged 4710 and 4940 kcal/d. Both men lost body weight, with the changes primarily reflecting loss of fat energy stores. The lighter man (Gjeldnes) gained lean mass, while the heavier man (Larsen) lost a small amount of lean mass and a relatively large amount of fat weight. Both men completed the trek with low-normal fat stores of approximately 13% body fat, indicating adequate energy intakes. Most physical performance measures showed trivial changes that were within the error of measurement and test reproducibility, indicating no significant loss of physical capacity as a result of prolonged exertion. However, anaerobic tests were significantly impaired following the trek, probably reflecting a

detraining effect and possibly including some component of fast twitch muscle loss as previously reported in other prolonged military ski treks. Endocrine markers of metabolic status including oral glucose tolerance tests indicated no functional impairments at the end of the trek. This study documents that well-trained and experienced long-distance ski-trekkers who eat a high-calorie diet can perform extremely long and arduous treks in severe cold and wind, with relatively minor and acceptable losses in lean body mass and physical capability.

INTRODUCTION

This study was part of a program to study the effects of prolonged exhaustive physical work, such as might be expected of elite soldiers on special missions (7, 11, 12). The goals of this study were to describe (a) the physical characteristics of two individuals who have been successful at long-distance, unsupported ski-trekking over snow and ice, (b) the changes in their performance capabilities caused by a prolonged trek, and (c) the associated performance changes with net breakdown or increases of regional and total muscle mass and bone mineral density.

The subjects of this study were two experienced, motivated, and highly fit polar explorers who were very different in size (total body mass, lean mass, fat mass, and height) and physical capabilities (absolute aerobic capacity, maximal single repetition lifting strength, anaerobic capacity, and power output). However, despite their physical differences, these two subjects covered the same distance, pulling sleds of similar mass, and consumed the same specially formulated calorie-dense diet. It was hypothesized that the larger, stronger subject would not experience the same adaptation to the physical work demand of the expedition as would the more moderately sized, less strong, but more aerobically fit subject. In other words, there would be a trend towards the mean, with the strong subject "detraining" and the weaker subject "training-up" to meet the demands of the expedition. Overall, either subject would be expected to loose fitness or detrain in the fitness components (strength, endurance) in which he received less training stimulus than he had been accustomed to before the trek and gaining fitness in those components for which the demands of the trek were higher than pre-trek levels. For example, a strong person of low aerobic fitness in a situation in which he doesn't have to work against large resistive loads very often, but must constantly do a lot of aerobic work will find himself loosing strength and gaining aerobic fitness. An alternate hypothesis was that both subjects would suffer significant physical performance decrements even if energy balance was maintained by adequate energy intake. This would be tentatively explained as a physical "overtraining" phenomenon, caused by incomplete repair of broken down tissue and incomplete rest and recuperation during a sustained effort.

The two men involved had already made a successful west-to-east unsupported crossing of Greenland, about a third of the distance of the planned south-to-north Greenland trek. The new trek involved an airdrop to the starting point, kayaking on the

sea to a southern island and back to the mainland, and traveling overland by skiing and walking while pulling sleds that weighed approximately 150 kg each at the beginning of the trek and diminished in weight as supplies were used. At the end of the trek, the two men returned to the U.S. Army Research Institute of Environmental Medicine (USARIEM), Natick, MA, to repeat pre-trek tests, enabling identification of trek-induced changes in physical performance and body composition.

A study (14) of Swedish ski troops on patrol covering 1500 km in 50 days and carrying 25 kg rucksacks, documented a selective decrease in Type IIa muscle fibers in the arm (-12%), but no changes in the leg muscles. The significance of such modest physiological changes in terms of practical physical performance outcomes was not measured. On the basis of these data, we hypothesized *a priori* that, with adequate energy intakes, there would not be any meaningful decrements in physical capability of the two men, or that any important changes would occur in upper body strength performance. If, instead, the study showed that these men lost significant performance capabilities, that would highlight the need for future studies to explore mechanisms of "overtraining" and pursue the development of countermeasures.

METHODS

TEST VOLUNTEERS

The two volunteers, Rune Gjeldnes and Torry Larsen, were trained as Norwegian Navy SEALs. As preparation for this trek, they had conducted a 700 km west-to-east trans-Greenland ski-trek in 1994 (Umanaq - Isertoq Expedition). The trek was planned by the subjects, Rune Gjeldnes (Subject R) and Torry Larsen (Subject T), as a well-publicized record breaking event. They invited a joint effort by Norwegian and U.S. military researchers to collect physiological data documenting the endurance effort.

VOLUNTEER BRIEFING

The volunteers gave their consent to be studied after being informed of the purpose, risks, and benefits of the scientific measurements to be made. This study was approved by the Human Use and Review Committee at USARIEM and endorsed by the Human Subjects Research Review Board at the U.S. Army Medical Research and Materiel Command, Fort Detrick, MD.

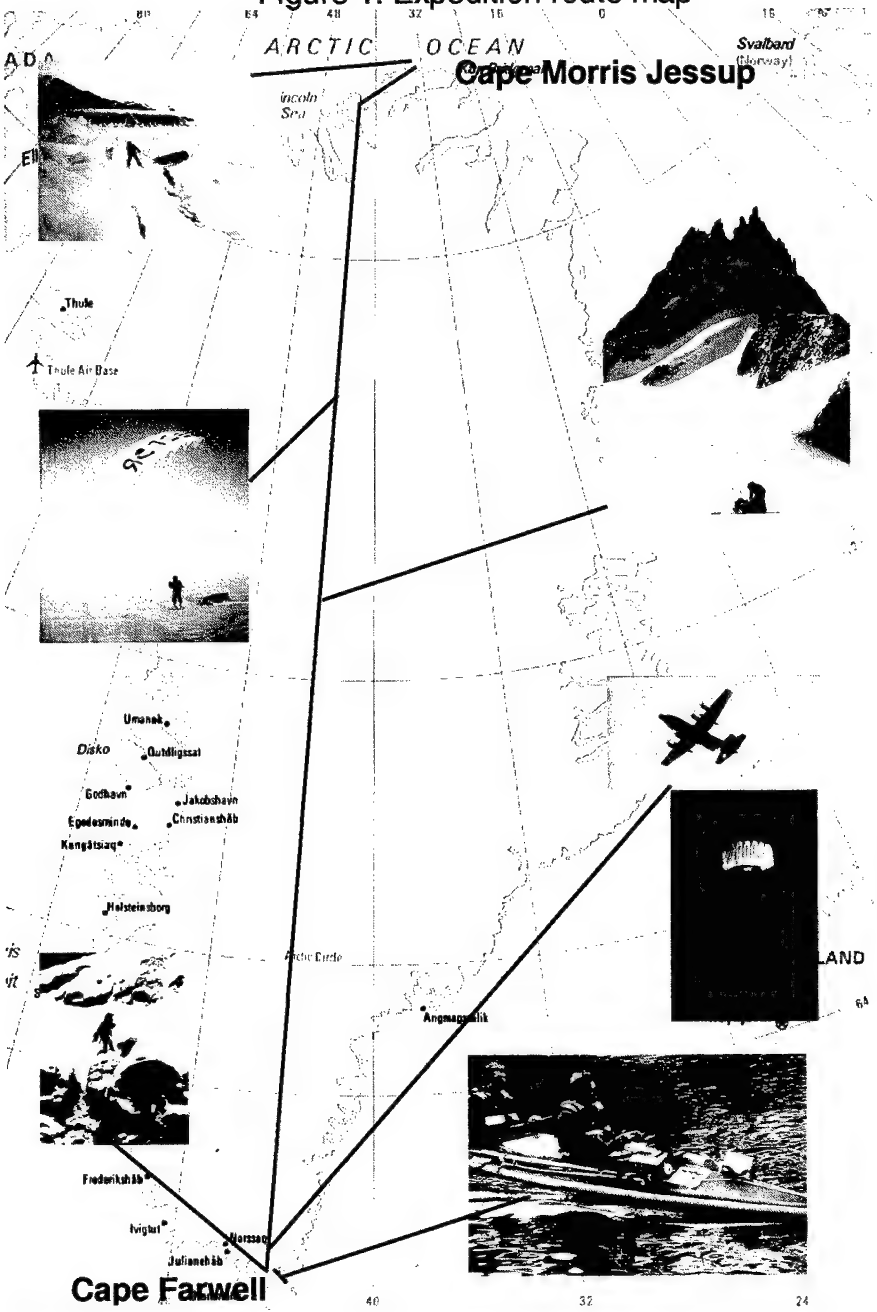
EXPEDITION SUMMARY

The G2 Expedition was a south-to-north ski-trek along the length of Greenland (Figure 1, Table 1). On 19 March, 1996, the volunteers and their equipment were air-dropped from a U.S Air Force KC-135 onto the southernmost tip of the inland ice plateau of Greenland.

From 20-23 March, the two explorers descended from the glacial plateau to the sea to begin paddling south to Cape Farewell, the southernmost point of Greenland. On 24 March they reached the sea, assembled a folding kayak, and paddled south. On 26 March, their kayak capsized and they were immersed in 1°C water for 12-15 minutes. With difficulty they returned to shore to dry themselves and their equipment. They continued south, but on 27 March, they encountered dense floating sea ice and decided to turn north for safety reasons.

They ascended to the inland ice plateau on 31 March and prepared for the ski-trek north. Departing north from the drop zone, each ski-trekker pulled a sled containing all of his equipment, food, and fuel for the projected 100-day duration of the

Figure 1. Expedition route map



trip (Figures 2 and 3), each of which had an initial mass of 150 kg.

From 1-16 April, the two volunteers traveled north, gradually climbing to the high inland ice plateau 2000 meters above sea level. From 17 April-15 May, they continued north over bleak and monotonous flat ice and snow. Weather records for this area and

time period indicate wind speeds of up to 31 m•s^{-1} (70 miles•hour^{-1}) with an average temperature of -15°C.

During the period from 16-31 May, the volunteers were able to take advantage of the prevailing katabatic winds which blow north up the middle of Greenland during

Table 1. G2 Trek Study timetable.

Dates	Trek progress and location	Study Notes
4-5 Mar	Underwent pre-trek testing at USARIEM	All tests
19 Mar	Parachuted onto the southernmost tip of the inland ice-plateau of Greenland	
20-23 Mar	Descended from the glacial plateau to the sea	
24 Mar	Kayaked south toward Cape Farewell	
26 Mar	Survived capsize of kayak and immersion in 1°C water for 12-15 minutes; returned to shore to dry	
27 Mar	Continued south but encountered dense floating sea ice; turned north	
31 Mar	Reached inland ice plateau and began ski-trek north	
1-16 Apr	Traveled north gradually climbing to the high inland ice plateau at an altitude of 2000 meters	DLW dosing #1 (1-15 Apr)
17 Apr-15 May	Continued north over monotonous flat sea of ice and snow; some weather delays	DLW dosing #2 (30 Apr-12 May)
16-31 May	Used parachutes to pull the sleds with prevailing katabatic wind; high rate of progress	DLW dosing #3 (21-27 May)
1-12 Jun	Descended from the inland ice plateau to Cape Morris Jessup for pickup by the expedition support team	
16-17 Jun	Post-trek testing at USARIEM	All tests

DLW: doubly-labeled water

Figure 2. Rune Gjeldnes and Torry Larsen on skis pulling their sleds on a typical G2 trek day

Figure 3. Rune Gjeldnes and Torry Larsen in their tent at a typical rest stop

springtime. They used steerable parachutes to pull themselves and the sleds north and made rapid progress, some days covering as much as 130 km.

From 1-12 June, they descended from the inland ice plateau via the Henson glacier and arced northeast to Cape Morris Jessup, the northernmost point of Greenland and the end of their ski-trek. The expedition support team picked them up at Cape Morris Jessup and transported them; within 4 days they were at USARIEM for the post-expedition testing.

EXPERIMENTAL DESIGN

Testing occurred 14 days prior to the start of the expedition and 4 days after the end of the trek. Testing took place at the USARIEM biomechanics laboratory, and at the indoor running track of the Dorothy Towne Field House, Wellesley College, Wellesley, MA.

BODY COMPOSITION

Body stature was measured using a stadiometer (GPM, Switzerland), and nude body mass (kg) was measured using an electronic platform scale (model 770 SECA Corporation, Columbia, MD). Fat free mass (FFM), total body and segment-specific fat mass, percent body fat, and bone mineral content were determined using a Lunar DPX-L dual energy X-ray absorptiometer (DXA) running software version 3.6 (Lunar Corporation, Madison, WI). During this procedure, the volunteer, dressed in shorts and T-shirt, lay face-up, laterally centered on a DXA scanner table, with the hands palm-downward. Velcro straps were used to keep the knees together and support the feet so they were plantar-flexed 45 degrees from vertical. Scanning proceeded in slices, 1-cm apart, from head to toe using the medium scanning speed, and took about 20 minutes for a whole-body scan.

Percent body fat was calculated from four skinfold sites (biceps, triceps, subscapular, suprailiac) using the equation of Durnin and Womersley (3). In addition, abdominal, thigh, and calf skinfolds were measured using a Harpenden Skinfold caliper (Holtain Ltd., Bryberian, Crymmych, Pembrokeshire, UK) and reported as the mean of two measurements.

Anthropometric girths were measured using an anthropometric tape (Lafayette Instrument, Lafayette, IN, USA) at the neck, shoulders, chest (inspired), chest

(expired), waist (navel), waist (natural), hips, biceps (relaxed), biceps (tensed with elbow flexed 90°), forearm, wrist, thigh (gluteal fold), thigh (maximum girth), thigh (measured at 1/2 the distance from knee to greater trochanter), thigh (measured 2 inches proximal from the patella), and calf (maximum girth).

Joint diameters were measured using a vernier caliper (GPM, Switzerland). The medial-lateral diameter of the right knee was measured at the widest point of the tibial plateau. The diameter of the right elbow was measured from the epicondyle to the epitrochlea. All anthropometric measurements were made both pre- and post-trek by the same experienced observer.

MAGNETIC RESONANCE IMAGING (MRI) STUDIES

Limb cross-sectional areas of muscle and fat were assessed using MRI (West Suburban Imaging Center, Wellesley Hills, MA). Images were obtained at mid-upper arm and upper leg on the right side of each subject before and after the trek. Percentage changes in muscle and fat cross-sectional areas were estimated using planimetry.

AEROBIC CAPACITY

Aerobic capacity was determined via open circuit spirometry during a continuous incremental treadmill running test. Oxygen uptake was measured using a computerized gas analysis system developed at USARIEM. The test subjects were connected to the analysis apparatus by mouthpiece and flexible tubing supported by headgear and overhead arm. They warmed up by running for 5 minutes at 8 km/h on the flat. After a 5 minute rest, the volunteers began running on the treadmill at 5% grade and a speed determined to be easy-to-moderate based on the volunteer's heartrate during the warmup run. Every 2 minutes, the treadmill speed was increased by 0.8 km/h without changing the treadmill grade. Subjects were considered to be at maximal oxygen uptake if, 1 minute after a speed increase, the volunteer had not increased oxygen uptake by at least 2 $ml \bullet kg^{-1} \bullet min^{-1}$.

ANAEROBIC POWER

Anaerobic power was measured via a Wingate cycle ergometer test (Cardiocycle computer-operated cycle ergometer, Ergometrx, Saint Paul, MN). After a 5 minute warm-up at 50% of the pedaling resistance used during the test the Wingate test

started. Five seconds before the start of the test, the subjects started pedaling as fast as possible. The pedaling resistance was increased in less than 1 second to a load of 5.8 joules per pedal revolution per kg of body mass. The subjects continued to pedal as fast as possible for the 30-second duration of the test. A computer calculated various measures of power and force generated during the exercise bout.

VERTICAL JUMP

Vertical jump was assessed using a Vertec vertical jump meter (Sports Imports Incorporated, Columbus, OH). After a 10-minute warm-up, each subject performed three maximal, standing, countermovement jumps. A countermovement jump is a jump that begins with the jumper standing upright with both feet on the ground and with both his hands held by his sides in an anatomically neutral position. He then bends forward at the hips while simultaneously squatting at the knees, and his hands are brought downwards and rearwards. This is the lowest point in this preparatory phase of the jump. From here the jumping motion begins with the jumper extending his knees and hips and swinging his arms forward and over his head reaching as high as possible. The highest of three jumps was used to determine the peak instantaneous power output (6).

ONE REPETITION MAXIMUM (1RM) STRENGTH MEASUREMENTS

To measure 1RM whole body strength, each subject performed a series of single repetition, two-handed box lifts to a height of 132 cm. Prior to each lift, the subjects were given 3 minutes of rest. The subjects performed incremental lifts until they failed twice at a given load or declined to continue lifting. For the lifting test, volunteers were instructed to use proper technique, including smooth lifting motion, left-right body symmetry, arched back, and use of the legs in preference to the back. Following a warm-up set, the volunteers were asked to perform the first attempt with a weight that could be lifted without much difficulty. The volunteer and experimenter then decided how much weight was to be tried on each subsequent attempt in order to reach a maximum within 5-8 attempts. The volunteers were asked to rest at least 1 minute between attempts and take as much time as needed to feel fully recovered from the previous attempt and to be ready for the next attempt.

REPETITIVE-SQUAT POWER OUTPUT TEST

To measure whole-body, strength-endurance capacity, the subjects performed a power output task consisting of repetitive squats with a 100 lb (45.5 kg) barbell. In this test the volunteer squats with a 45.5 kg barbell, lifting the weight 0.36 m per repetition, at a metronome-cued rate of 0.625 repetitions/s (37.5 repetitions/min), resulting in a power output of 100 watts exerted by the lifter on the bar. The test conditions were empirically chosen so that the test should take no longer than 10 minutes, even for a large, fit, test volunteer. Yet the weight was light enough for even smaller, less fit volunteers to do at least a few repetitions. The test was conducted inside a squat-rack so that, even if the volunteer could not rise from the squat position, the bar would come to rest on the rack and the volunteer could safely get out from under the bar. The test was completed when a subject lagged behind the pace for two consecutive lifts, even after verbal exhortation.

External power output during the test was calculated as:

$$
\begin{aligned}
\text{power}_W = \text{force}_N \times \text{velocity}_{m \cdot s^{-1}} & \\
&= (\text{bar mass}_{kg} \times \text{accel of gravity}_{m \cdot s^{-2}}) \cdot (_{m \cdot rep^{-1}}) \cdot (_{rep^{-1} \cdot s}) \\
&= (45.36_{kg} \times 9.80368_{m \cdot s^{-2}}) \cdot (0.36_{m \cdot rep^{-1}}) \cdot (0.625_{rep^{-1} \cdot s}) \\
&= 100 \text{ watts}
\end{aligned}
$$

CART PULL

The subjects performed a 3.2 km cart-pulling test as a test of aerobic fitness/performance that most closely resembled the sled pulling of the expedition. The cart they used was attached to them using a waist harness and rolled on two bicycle wheels. The total load pulled during the test was 70.5 kg. The subjects were timed as they pulled the cart as fast as possible around a 200-meter indoor track located at the Dorothy Towne Field House of Wellesley College, Wellesley, MA.

OBSTACLE COURSE

Subjects were timed negotiating a 6-station obstacle course with and without a 34-kg rucksack. An electronic timing system (Brower Timing Systems, Salt Lake City, UT) was used to time the volunteers on the total course and each of the obstacles. The volunteers began the course from a cued standing start, with the first obstacle being a set of five 46 cm high plastic hurdles spaced 2.1 m apart. The second obstacle required

the subjects to run a zigzag pattern through a field of 9 plastic cones staggered such that adjacent cones were 1.5 m apart laterally and 3.4 m apart along the 26.8 m length of the course segment. Third was a low-crawl obstacle made of wood and rope, 61 cm high, 91 cm wide, and 3.7 m long. Without a backpack on, the volunteers could crawl on their hands and knees, but with a pack on, they had to stay close to the ground and move along in a crab-like manner. After the low-crawl, the volunteer proceeded to a horizontal pipe 3.7 m long, suspended 1.42 m above the ground. The subjects traversed the length of the pipe while hanging by their arms and legs. The majority of the weight was supported by the hands and arms, which also had to be used to pull the body along the pipe. The fifth obstacle was a 137 cm high smooth wooden wall. Subjects finished the obstacle course with a 28.7 m straight sprint. Each subject was allowed familiarization/practice time on the course prior to testing.

ENERGY EXPENDITURE

The subject's energy expenditure was assessed in three separate 7-15 day periods during the expedition. Total daily energy expenditure (TDEE) was assessed by the DLW technique, using previously reported methods for military field studies (2). Pre-measured DLW doses were self-administered three times during the expedition: at the beginning and end, where terrain is difficult and elevation changes rapidly, and during the middle portion where the terrain was fairly level and representative of most of the trek. Each dose contained, per kg of each volunteer's total body water, 0.16 g of ^2H_2O (Cambridge Isotope Laboratories, Andover, MA) and 0.25 g of $H_2{}^{18}O$ (Isotec Inc., Miamisburg, OH).

On the morning of day 0, the two volunteers, who had refrained from eating or drinking for at least 12 hours, collected a baseline sample of their first-void urine. After baseline saliva samples were collected, the subjects drank their dose of DLW, as well as about 100 ml of canteen water used to rinse the dose container. Saliva samples were collected 3 and 4 hours after the dose to determine TBW. First morning void urine samples were collected on Day 1, Day 7, Day 13, and Day 15.

Isotopic analyses were performed as previously described (2). Briefly, the ^{18}O abundances were measured by equilibration of fluid with CO_2. Measurements were done in duplicate with a standard deviation of 0.15 ‰. Deuterium abundances were measured by the zinc reduction method. Measurements were performed in duplicate

with a standard deviation of 1.2 ‰. Isotope enrichments were calculated by taking the arithmetic difference between the enrichment of each sample and the respective pre-dose sample.

Total daily energy expenditure was calculated using a two-point method. Baseline isotopic enrichments were assumed to be constant. The rate of CO_2 production was calculated using the equation:

$$rCO_2 = (N/2.078)(1.007k_O-1.041k_H)-0.0246rH_2O_f$$

where N is the total body water calculated from the ^{18}O enrichment in the 4 hour saliva sample (or average of initial and final 4 hour saliva samples if TBW is expected to change), and rH_2O_f is the rate of fractionated evaporative water loss, which is estimated to be $1.05N\ (1.007k_O - 1.041k_H)$. Energy expenditure was calculated from the rate of CO_2 production using metabolic fuel respiratory quotients calculated from food intake and body energy store combustion and conventional calorimetric relationships. Standard factors were used to correct for isotope fractionation in respiratory and cutaneous water efflux.

ESTIMATION OF ENERGY INTAKE

Energy intake was indirectly estimated from the pre-packaged meals that the subjects consumed during the course of the expedition (8). The caloric content of these meals was determined prior to the expedition to assure the subjects would carry enough rations to meet their needs. Separate meal rations for breakfast, lunch, dinner, and a daily chocolate portion had been prepared for the projected 100-day duration of the trek. The caloric values of these meals are shown in Table 2. The daily energy intake estimates were made on the basis of these values, with the assumption that the entire daily ration was consumed; the participants reported that this was the case. The diet had been planned based on experience gained during the 1994 Umanaq - Isertoq Expedition Across Greenland.

Table 2. Estimated energy intake of the trekkers, based on planned daily rations

Ingredients	Weight (grams)	Energy (kcal)	Macronutrient composition (g)		
			Carbo.	Protein	Fat
BREAKFAST					
Boiled oats	115	510	86	22	7
Nuts	15	95	3	3	9
Sugar	20	81	20	0	0
Soybean oil	75	660	0	0	75
Dried milk	15	55	8	5	0
TOTAL	240	1400	117	30	91
LUNCH					
Rolled oats	110	490	82	21	7
Blueberry soup	25	95	24	0	0
Raisins	25	75	20	1	0
Nuts	60	375	13	11	34
Soy oil	100	880	0	0	100
TOTAL	320	1915	139	12	141
Chocolate	150	775	86	11	48
SUPPER					
Dehydrated dinner entree	200	1000	143	42	27
Soy oil	100	880	0	0	100
Supper total	300	1880	143	42	127
Daily total	**1010**	**5970**	**485**	**95**	**612**
Energy source (% of total kcal)			**32**	**7**	**61**

ENDOCRINE MARKERS OF METABOLIC STATUS

Glucose tolerance and insulin resistance were assessed before and after the trek using a standard glucose tolerance test with a 100 g load and serum samples collected at -15, 0, 10, 20, 30, 45, 60, 90, 120, and 150 minutes. Baseline, peak, and area under the curve (AUC) values were determined for glucose, insulin, and c-peptide, measured using standard clinical test methods. Tests were conducted on fasted subjects at the same time of the morning in pre- and post-trek testing. Four other key markers of metabolic and osmoregulatory status were also measured: testosterone, cortisol, prolactin, and luteinizing hormone (LH) using standard radioimmunological tests, as previously described (13, 14). Averages of three measurements collected during the first 25 minutes of each study (the -15, 0, and 10 minute sampling points during the OGTT) are reported. Values were compared to normal clinical ranges.

RESULTS

ANTHROPOMETRIC CHARACTERISTICS AND BODY COMPOSITION

Height, weight, and DXA-based measures of total percent body fat, fat mass, lean mass, and bone mineral content, as well as anthropometric measures (skinfold thickness, circumferences, and breadths), are shown in Tables 3 and 4, respectively, for the pre- and post-trek study periods. DXA regional data for arms, legs, and trunk for the two subjects are shown in Table 5. Both men lost body mass, with the changes primarily reflecting loss of fat energy stores (Table 3). The lighter man (Subj R) gained lean mass, while the heavier man (Subj T) lost a small amount of lean mass and a relatively large amount of fat weight. Both men completed the trek with low-normal fat stores of approximately 13% body fat, indicating adequate energy intakes to fuel energy requirements without substantial sacrifice of body energy stores. The loss of 1.6 and 7.0 kg fat in these two men corresponds to energy deficits of 14,000 and 63,000 kcal, or an energy intake shortfall of approximately 165 and 730 kcal/d for the two men.

The FFM estimates produced by the two independent methods of DXA and total body water were comparable. Total body water estimated by isotope dilution was 51.0 L (Subj R) and 60.1 L (Subj T) at the start of the trek. Using assumptions of normal average FFM hydration (73% water by mass), the total body water methods predicted starting FFMs of 69.2 kg (Subj R) and 82.3 kg (Subj T). By DXA, these starting levels were measured as 70.5 kg (Subj R) and 81.0 kg (Subj T), indicating a good match between the two methods. The procedures were performed two weeks apart.

Table 3. Body composition measurements by DXA and skinfolds of the trekkers

Parameter	Subject R			Subject T		
	Pre-trek	Post-trek	Change	Pre-trek	Post-trek	Change
Age (yrs)	25	---	---	25	---	---
Height (cm)	179	---	---	193	---	---
Body weight (kg)	82.5	81.4	-1.1	100.4	91.8	-8.6
DXA						
Body fat (%)	14.5	12.7	-1.8	19.3	13.5	-5.8
Fat weight (kg)	12.0	10.4	-1.6	19.4	12.4	-7.0
Fat-free mass (kg)	66.7	67.3	0.6	76.6	75.2	-1.4
Bone mineral (kg)	3.80	3.76	-0.04	4.41	4.24	-0.17
SKINFOLD THICKNESSES (mm)						
Bicep*	5.5	4.7	-0.8	7.8	6.7	-1.1
Tricep*	8.2	8.4	0.2	9.4	8.4	-1.0
Subscapular*	10.2	10.4	0.2	15.0	12.7	-2.3
Suprailiac*	7.6	8.3	0.7	14.2	8.8	-5.4
Abdomen	25.7	14.8	-10.9	38.8	20.6	-18.2
Thigh	11.4	10.5	-0.9	20.9	17.6	-3.3
Calf	8.6	10.7	2.1	11.0	13.6	-2.6
Body fat (%)*	13.4	13.5	0.1	18.0	15.2	-2.8

(*Durnin-Womersley equation)

Table 4. Anthropometric circumferences and joint diameters of the trekkers

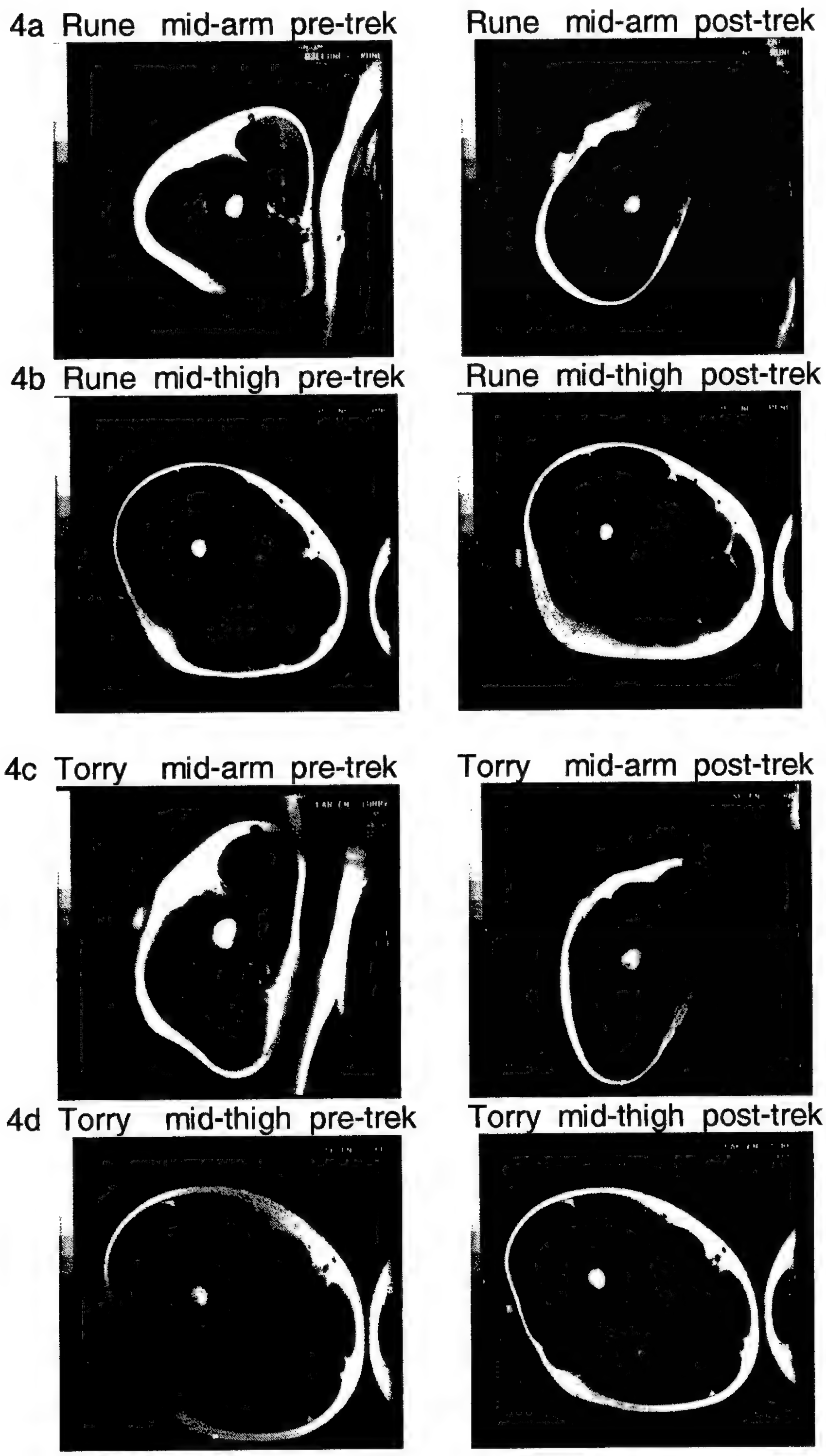
Parameter	Subject R			Subject T		
	Pre-trek	**Post-trek**	**Change**	**Pre-trek**	**Post-trek**	**Change**
CIRCUMFERENCES (cm)						
Neck	38.5	37.4	-1.1	40.8	38.5	-2.3
Shoulders	119.0	118.0	-1.0	121.1	125.4	4.3
Chest (expanded)	106.2	105.0	-1.2	106.7	104.3	-2.4
Chest (exhaled)	104.9	102.2	-2.7	104.2	101.8	-2.4
Waist at navel	86.7	85.7	-1.0	94.3	88.8	-5.5
Natural waist	85.4	84.8	-0.6	92.6	86.6	-6.0
Hips	103.0	101.8	-1.2	108.7	104.7	-4.0
Biceps (relaxed)	30.2	30.5	0.3	33.2	31.9	-1.3
Biceps (flexed)	32.9	33.2	0.3	35.3	35.2	-0.1
Forearm	28.5	28.2	-0.3	30.3	29.4	-0.9
Wrist	17.6	17.5	-0.1	17.2	17.4	0.2
Thigh (gluteal fold)	60.5	58.9	-1.6	65.6	62.4	-3.2
Thigh (maximal girth)	60.9	59.2	-1.7	66.5	62.4	-4.1
Thigh (midpoint)	54.4	56.8	2.4	57.9	59.2	1.3
Thigh (above knee)	43.9	42.1	-1.8	44.3	45.8	1.5
BREADTHS-JOINT DIAMETERS (cm)						
Elbow	7.3	7.3	0.0	7.6	7.9	0.3
Knee	10.5	9.8	-0.7	10.9	9.6	-1.3

Table 5. DXA-measured regional body composition measurements of the trekkers

Parameter	Subject R			Subject T		
	Pre-trek	Post-trek	Change	Pre-trek	Post-trek	Change
ARMS (kg)						
Total mass	9.5	9.7	0.2	12.0	10.3	-1.7
Fat mass	1.6	1.4	-0.2	2.4	1.3	-1.1
Fat-free mass	7.9	8.3	0.4	9.6	8.9	-0.7
LEGS (kg)						
Total mass	27.5	25.8	-1.7	30.9	30.6	-1.7
Fat mass	4.0	3.3	-0.7	5.7	4.4	-1.3
Fat-free mass	23.6	22.5	-1.1	25.2	26.2	-1.0
TRUNK (kg)						
Total mass	36.5	37.0	0.5	47.7	41.7	-6.0
Fat mass	5.8	5.0	-0.8	10.5	6.0	-4.5
Fat-free mass	30.8	32.0	1.2	37.3	35.7	-1.6

Muscle MRI cross-sectional images are shown in Figure 4. The combined muscle and bone areas showed changes, with Subj T experiencing losses of 0.48% in right mid-arm and 14.2% in the right mid-thigh. Subj R showed a 0.86 % loss in the muscle and bone area of the right mid-thigh and a gain of 2.45% in the right mid-arm. The changes in fat area in both men decreased significantly in the arm by 65.6% in Subj T and 31.0% in Subj R. These reductions are clearly apparent in the images (Figure 3). The fat area in the leg decreased by 18.2% in Subj T and increased by 26% in Subj R.

Figure 4. Cross sections of mid-arm and mid-thigh, pre- and post-trek for the two subjects.



Pre-post changes in cross-sectional area

Muscle and Bone area
2.45%

Fat area
-31.0%

Muscle and Bone area
-0.86%

Fat area
26.0%

Muscle and Bone area
-0.48%

Fat area
-65.6%

Muscle and Bone area
-14.2%

Fat area
-18.2%

PHYSICAL PERFORMANCE MEASURES

Aerobic capacity data, based on treadmill testing, are shown in Table 6. Maximal aerobic capacity varied within the range of test-retest reliability, with values for one subject slightly increasing and the other slightly decreasing. The measured values of 64 and 60 ml/kg/min indicated above average aerobic fitness levels relative to male age group norms.

Table 6. Aerobic capacity measurements of the trekkers

Parameter	Subject R			Subject T		
	Pre-trek	**Post-trek**	**Change**	**Pre-trek**	**Post-trek**	**Change**
Aerobic capacity (treadmill protocol)						
$\dot{V}O_{2\,max}$ ($l \bullet min^{-1}$)	5.34	5.51	0.17	6.11	5.27	-0.84
$\dot{V}O_{2\,max}$ ($ml \bullet kg^{-1} \bullet min^{-1}$)	64.0	67.7	3.7	60.3	56.6	-3.7
HR at $\dot{V}O_{2\,max}$ ($b \bullet min^{-1}$)	206	217	11	206	200	-6

Anaerobic power data, based on Wingate cycle ergometry and vertical jump testing are shown in Table 7. The trek resulted in a meaningful decrement in peak power, especially for the larger of the two subjects. Post-trek values, however, were still above average. A decline in vertical jump peak power was also observed (Table 7), with a greater than 15% change in vertical jump height and calculated peak power. Thus, both independent tests indicate a meaningful reduction in anaerobic power as a result of the trek.

Table 7 Anaerobic power based on Wingate cycle ergometry and vertical jump testing

Parameter	Subject R			Subject T		
	Pre-trek	**Post-trek**	**Change**	**Pre-trek**	**Post-trek**	**Change**
Anaerobic power (Wingate protocol)						
Peak Power (W)	889	754	-135	1129	866	-263

Peak Power (W/kg)	10.4	9.2	-1.2	11.1	9.3	-1.8
Pk Pwr (W/kg FFM)	12.3	10.6	-1.7	13.8	10.6	-3.2
Minimum Power (W)	514	5.3	-11	655	566	-89
Average Power (W)	761	673	-88	910	740	-170
Peak power output (vertical jump)						
Jump height (cm)	59.7	50.8	-8.9	50.8	40.6	-10.2
Peak power (W)	4915	4289	-626	4962	4067	-895

Strength and strength-endurance measurements are shown in Table 8. These measures again indicate the high level of physical fitness of the two men. The one repetition max lifts were 85 and 103 kg for the two men, approximating the lifters body weights, reflecting well above average strength. The pre-post trek changes fell within the variability of these tests.

Table 8. Strength and strength-endurance measurements of the trekkers

Parameter			**Subject R**			**Subject T**
	Pre-trek	**Post-trek**	**Change**	**Pre-trek**	**Post-trek**	**Change**
Strength test (maximal lift)						
1-RM 132 cm lift (kg)	85.3	90.1	4.8	103.4	89.2	-14.2
Strength endurance test (repetitive lift)						
100 lb repetitive squat (# reps)	146	123	-23	55	66	11

A unique cart-pull test was devised to represent the typical exercise performed during the trek: dragging a sled via a line attached to the waist. These measurements did not change in a meaningful way as a result of the trek (Table 9). In addition, an electronically timed indoor obstacle course revealed no changes greater than the variability of the test (Table 9).

Table 9. Practical physical performance measurements of the trekkers

Parameter	Subject R			Subject T		
	Pre-trek	Post-trek	Change	Pre-trek	Post-trek	Change
Cart pull (3.2 km, 70.5 kg cart, min:sec)						
1.2 km split	4:34	4:48	0:14	5:00	5:38	0:38
2.4 km split	9:38	9:55	0:17	10:05	11:17	1:12
3.2 km finish	13:00	13:16	0:16	13:22	14:38	1:19
Instrumented obstacle course - unloaded (sec)						
Total time	33.4	33.5	0.1	35.8	36.9	1.1
Hurdles	3.0	3.2	0.2	3.6	4.2	0.6
Weave cones	7.7	7.3	-0.4	8.1	8.4	0.3
Low crawl	5.8	5.8	0.0	6.4	6.2	-0.2
Pipe	8.0	7.9	-0.1	8.4	8.5	0.1
Wall	3.6	4.0	0.4	4.3	4.2	-0.1
Sprint	5.3	5.2	-0.1	4.9	5.4	0.5
Instrumented obstacle course - carrying 34.4 kg backpack (sec)						
Total time	57.7	56.2	-1.5	48.4	53.0	4.6
Hurdles	3.8	4.2	0.4	4.4	4.8	0.4
Weave cones	9.2	9.3	0.1	8.9	9.6	0.7
Low crawl	12.7	11.8	-0.9	10.2	11.4	1.2
Pipe	16.0	18.2	2.2	13.3	13.2	-0.9
Wall	6.3	6.4	0.1	5.4	7.3	1.9
Sprint	6.7	6.4	-0.3	6.2	6.8	0.6

ENERGY EXPENDITURE

The highest TDEE occurred at the measurements taken in the first sampling period from 1-15 APRIL. The conditions at this time were arduous because of heavy damp snow, and when the sleds were heaviest because the supplies were not yet used. During this initial period, peak levels reached 6750 and 8260 kcal/d for the two men. In a 2-week sample period during the main period of travel on flat terrain (30 APRIL – 12 MAY), TDEE was 3500-3850 kcal/d. In the last testing period (21-27 MAY), TDEE averaged 4710 and 4940 kcal/d.

ENDOCRINE MARKERS OF METABOLIC STATUS

Testosterone and cortisol levels were entirely within normal limits, indicating no lasting alterations in metabolic status (Table 10). Acute energy deficits would be expected to reduce testosterone and large chronic deficits would acutely raise cortisol. The pulsatile pituitary hormones, prolactin (a marker of osmoregulatory status) and LH (a marker of gonadal dysfunction) were also within normal limits.

Table 10. Endocrine markers of metabolic status for the trekkers

Parameter	Subject R		Subject T	
	Pre-trek	Post-trek	Pre-trek	Post-trek
Serum concentrations (average of 3 samples collected over 25 minutes)				
Testosterone (nmol/L)	22.4	18.1	27.2	26.5
Cortisol (nmol/L)	330	278	404	267
Prolactin (ng/mL)	9.5	10.0	7.3	7.4
LH (mIU/mL)	1.7	0.8	1.7	2.0

Fasted glucose, peak glucose responses, and AUC remained normal and were very reproducible before and after the trek. Insulin and c-peptide responses to the same glucose load were reduced for both men at the end of the trek, suggesting an improved metabolic efficiency (Table 11).

Table 11. Endocrine responses to a 100 g oral glucose load for the trekkers

Parameter	Subject R		Subject T	
	Pre-trek	Post-trek	Pre-trek	Post-trek
Oral glucose tolerance test results (100 g dose)				
Glucose baseline (mmol/L)	4.8	4.9	5.6	5.1
Glucose peak levels (mmol/L)	7.4	8.9	9.2	8.9
Glucose AUC (mmol/L x 2 h)	752	804	818	755
Insulin baseline (umol/L)	5.4	5.3	6.3	5.0
Insulin peak levels (umol/L)	76.7	52.7	63.0	35.0
Insulin AUC (umol/L x 2 h)	5,555	3,248	4,000	1,652
C-peptide baseline (pmol/L)	595	563	550	474
C-peptide pk levels (pmol/L)	2,518	1,718	1,683	1,718
C-peptide AUC (pmol/L x 2 h)	217,560	90,705	152,370	132,720

DISCUSSION

It appears that the combination of good preparation (physical and logistical) and a diet specially tailored to the energetic demands of the expedition helped minimize the losses in body mass and lean mass that often accompany long duration, severe physical activities in harsh environments. Subject T's moderate losses of body mass (8.60 kg) and lean mass (1.44kg) and Subject R's minimal body mass loss of 1.02 kg and his gain of lean tissue (0.623 kg) demonstrate that their diet and preparedness were appropriate for this extreme setting. This is especially striking when these subjects are compared to Army Ranger students who have lost more than 10% of body weight during a 64-day training course, suffering substantial physical performance decrements (4, 7, 11). The difference is that Ranger students are intentionally food-

deprived, while the subjects of this study made every attempt to ensure adequate energy intake.

The trekker's TDEEs varied over a wide range. The lowest TDEEs of 3500-3850 kcal/d were observed during the easiest part of the trek when the snow was hard (easier pulling conditions), the supplies carried in the sleds were nearly 50% consumed (less load to pull), and the trekkers were using the wind to pull them north. The highest TDEEs of 6750-8260 were seen during the early ascent onto the central Greenland plateau. At that time the ambient temperatures were near 0°C making the deep snow soft and more difficult to pull the sleds through. Additionally, the sleds were fully loaded at this early point in the trek. These TDEE levels bracket those that have been previously observed in soldiers working hard for prolonged periods of time (sustainable average of ~4000 kcal/d, with peak levels of ~6000-8000 kcal/d observed) and for the shorter duration Tour de France, which is believed to approach the upper limit of sustainable peak performance (7000 kcal/d).

The feeding plan for the trek provided 6,000 kcal/d for each man, an amount that was close to the needs of Subject R but 730 kcal/d too little for the larger Subject T, who had to support the metabolic requirements of 10 kg more lean mass. The accounts of some other polar expeditions show a pattern of marked loss of body mass (17, 20), and these can be attributed to large negative energy balances. In endurance events where the food supply is not limited, performance is well-sustained even as individuals achieve what may represent the upper limits of energy expenditure. This has been studied in the Tour de France, where cyclists averaged 7,000 kcal/d energy expenditure over 22 days without weight loss (5, 15, 23). Adequate energy intake is essential for high levels of sustained workload, with lower intakes directly proportional to lower ceilings of sustained productivity in manual laborers such as coal miners, construction workers, steel workers, and sugar cane cutters (1). This was the basis of B.M. Marriott's 1995 report on "Not Eating Enough - Overcoming Underconsumption of Military Operational Rations"(9).

Although both volunteers pulled sleds with equivalent loads, traversed the same distances over the same terrain, and ate nearly the same amount of food, they reacted to these challenges in very different ways. It is possible that because of the differences in their physical and physiological status at the start of the expedition, Subject R had to work at an appreciably higher percentage of his aerobic capacity and his strength. This

may have resulted in a "training" environment for Subject R and a "detraining" situation for Subject T. It is interesting to note that in the Wingate test, both subjects finished the expedition with the same peak power per kg of lean mass, suggesting a regression to the mean demands of the trek. The reduction in anaerobic power of both men suggests physiological changes that occur in all individuals with high volume endurance workloads that adaptively transform muscle to favor Type 1 slow twitch metabolism and/or selectively permit Type 2 fast twitch muscle to degrade. This was observed in ski troops by Schantz, et al. (16). A reversal of this phenomenon (increase in Type 2 fast twitch muscle and improvement in muscle power) has been observed in swimmers when they taper down their training volume over several weeks before competition (21).

This expedition represented a newly documented upper limit of performance for unsupported travel in cold regions. This study also fills a knowledge gap in defining the problems associated with prolonged physical performance. A previous study by Dr. Mike Stroud (Defence Research Agency, U.K.) gathered extensive biochemical and energy balance data on two men (Stroud and Sir Ranulf Fiennes) during an attempted crossing of Antarctica (18). The study examined changes in energy balance and thermogenesis, as Fiennes and Stroud retraced the route of Robert Falcon Scott's South Pole expedition of 1910-1912 (19). The main reason that Fiennes and Stroud could not complete the crossing was failure to take in enough calories to fuel their strenuous daily activities, with intakes of approximately 4800 kcal/d and actual requirements measured by DLW sometimes double this amount (20). Physical performance was substantially reduced in these men, including both strength and aerobic capacity. These changes accompanied large weight losses, including 7.8 and 9.3 kg FFM losses in the two men (18).

The Danish military still patrols Greenland by dogsled and has extensive experience (since 1951) in successfully surviving long treks without weight loss or notable decrements in performance. However, they have prepositioned supply depots along the route and use dogs to help pull the two-man patrol sleds (22).

An earlier successful crossing of Greenland (East-West) by Fritjof Nansen involved a shorter route than in the current study (South-North), but used similar strategies including the limited application of sails to help move the 220-pound sleds (10). The men were exhausted and somewhat apathetic at the end of the expedition, consistent with the experiences of soldiers completing U.S. Army Ranger training

before rest and recovery (4).

Physical performance was significantly reduced in Army Ranger students as a result of training, with 20% declines in lift strength and peak power, based on vertical jumping. However, these effects occurred in men following deliberate food restriction and substantial weight losses averaging 12%-16% of body weight in initially non-overweight men (7, 11). It should be noted that even with this large reduction in performance, the high level of fitness of these men at the start of their training buffered the changes, reducing these men to average soldier physical strength at the end of training.

CONCLUSIONS

These trekkers were well prepared physically and logistically. Their physical training regimen enabled them to meet the demands of the trek. Their losses of aerobic capacity might be interpreted as either the result of athletic detraining due to a lack of training stimulus, or as a result of over-training. Conversations with the trekkers in the year after the expedition indicate that they recovered their aerobic, anaerobic, and strength capabilities with a return to their normal training regimen and diet. This information leads one to believe that the changes in performance that occurred during the trek were not due to over-training, a condition which often results in a very long, slow return to fitness.

The diet these trekkers consumed provided them with enough caloric throughput as well as macro- and micro-nutrients so that they experienced only moderate losses in body fat stores and only moderate changes in physical performance.

The data collected during this study paints a picture of 2 sojourners who were physically well trained, and who brought not only enough food, but the correct balance of macro- and micro-nutrients to see them through the rigors of this expedition without appreciable losses of body mass or decrements in physical performance. This ski-trek is to this day the longest distance, unsupported foot-journey ever recorded.

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